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TECHNICAL REPORT 4995

GROUND SHOCK EFFECTS FROM ACCIDENTAL EXPLOSIONS

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NOVEMBER 1976



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TABLE OF CONTENTS

	Page No.
Introduction	1
Objectives	1
Design Criteria	1
Ground Shock Phenomenology	2
Prediction Methods	4
Approach	4
Findings	5
Prediction Equations	8
Design Implications	11
Inhabited Buildings	14
Magazines	15
Design Recommendations	18
Deficiencies	22
Recommendations for Further Study	24
Conclusions	25
Acknowledgments	26
References	27
Bibliography	29
Appendix - Sample Problem	33
List of Symbols	41
Distribution List	43
Tables	
1 Recommended prediction equations for air-blast-induced ground motion	9

2	Recommended prediction equations for direct-induced ground motion	12
3	Mass density for typical soils and rocks	19
4	Typical seismic velocities for soils and rocks	20

Figures

1A	Superseismic ground shock	3
1B	Outrunning ground shock	3
2A	Predicted and measured peak air-blast-induced displacements	10
2B	Predicted and measured peak air-blast-induced velocities	10
2C	Predicted and measured peak air-blast-induced accelerations	10
3A	Maximum direct-induced horizontal particle velocity; distant plain event 6	13
3B	PACE 450-kg (1,000-lb) tangent-above shot data, vertical velocity	13
3C	Peak horizontal (outward) acceleration versus distance from the mineral rock event	13
4	Tolerance of stiff-legged standing persons to short-duration vertical shock motions	17
5	Typical shock spectrum plot	21

INTRODUCTION

Objectives

This study was initiated to provide a better understanding of the significance of ground shock in designing structures to resist the effects of accidental explosions. The results of the effort are intended to supplement the design criteria of the tri-service manual, Structures to Resist the Effects of Accidental Explosions (Reference 1). Specific objectives of this effort are:

1. Establish semi-empirical methods and design aids for ground shock prediction.
2. Determine the effect of ground shock on personnel, structures, and equipment, especially as related to designs based on the tri-service manual.
3. Recommend testing and studies needed to supplement available information for determining ground shock and its effects.

Design Criteria

The criteria for Reference 1 provide extensive data on air blast and fragmentation phenomenology. Extensive treatments of various burst conditions, charge confinement configurations, reflection conditions, and fragmentation characteristics are included. Much of the phenomenology can be described by closed-form analytical methods or by numerical methods based on basic physical principles. Extensive experimental efforts have verified the data, and these efforts were justified by the fact that nearly all designs are controlled by these foregoing criteria.

The publication also contains guidance for the design of structures to resist the effects of air blast and fragmentation. Elastic and inelastic response of structures to side-on and reflected pressures is treated in great detail. The design of barriers to stop high-speed fragments is also treated in detail. These efforts are justified by the fact that over-pressure loads and fragment impact are critical survivability parameters.

Little effort has been devoted to the description of ground shock phenomenology or to the design of structures to resist ground shock effects. The subject is treated briefly in paragraph 10-9 of Reference 1, but no quantitative data are presented on prediction methods; however, personnel and equipment shock tolerances are treated in paragraphs 3-7 and 3-8.

A quantitative description of ground shock would be most helpful in evaluating its significance in specific cases. With this knowledge a designer could determine the significance of these effects. The intent of this study is to provide the designer with the necessary tools to make that decision.

Ground Shock Phenomenology

Ground shock results from energy imparted to the ground by an explosion. Some of the energy is transmitted through the air in the form of air-blast-induced ground shock and some is transmitted through the ground as direct-induced ground shock. Each of these phenomena and their interaction will be briefly described to provide a review for the reader. Excellent detailed descriptions of ground shock phenomenology are contained in References 2 and 3.

Air-blast-induced ground shock results when the air-blast shock wave compresses the ground surface and sends a stress pulse into the underlying media. The magnitude and duration of the stress pulse in the ground depends on the character of the air-blast pulse and the ground media. Generally the air-blast-induced ground motions are downward. They are maximum at the ground surface and attenuate with depth. However, the presence of a shallow water table, a shallow soil-rock interface, or other discontinuities can alter the normal attenuation process. Generally, however, the properties of the side-on overpressure pulse and the surface soil layer determine the character of air-blast-induced ground shock on aboveground structures.

Direct-induced ground shock results from the explosive energy being transmitted directly through the ground. The term as it is used in this report includes both true direct-induced motions and cratering-induced motions. The latter are generally of longer duration and are generated by the crater formation process in cratering explosions. Both of these phenomena tend to be of longer duration than air-blast-induced ground shock, and the waveforms tend to be sinusoidal.

The net ground shock experienced by a point on the ground surface is a combination of air-blast- and direct-induced shock. The relative magnitudes and sequencing of the motions are functions of media and absolute distance from the point of detonation. At ranges close to the blast, the highly compressed air permits the air-blast shock front to propagate at speeds greater than the seismic speed of the ground. In this region, the super-seismic region, the air blast arrives before the direct-induced ground shock. As the air-blast shock front moves farther from the blast point, it slows, and the direct-induced ground shock catches and "outruns" the air blast. This latter region is called the outrunning region. Waveforms in the outrunning region are generally a complex combination of both waveforms. Relative phasing of each portion of the motion can be estimated by calculating arrival times of each wave. The arrival time of the air blast can be determined from the data in Reference 1, and the arrival time of the direct-induced wave can be estimated by assuming the ground shock travels at the seismic velocity of the ground media. Examples of net ground motions in both regions are illustrated in Figure 1.

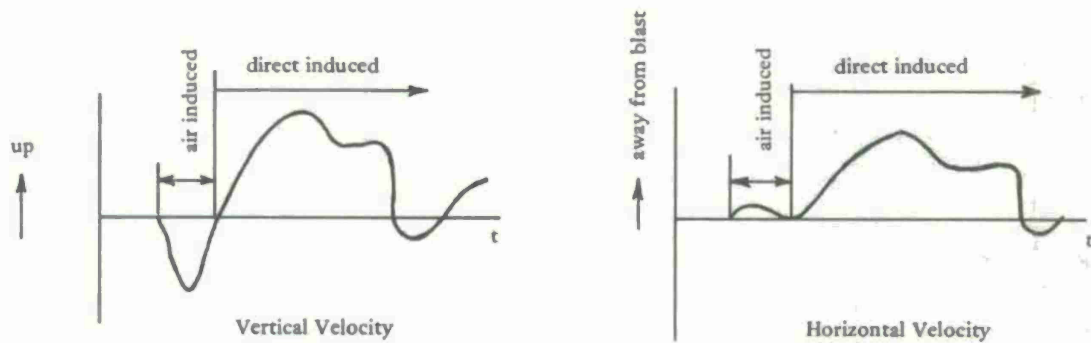


Fig 1a. Superseismic ground shock

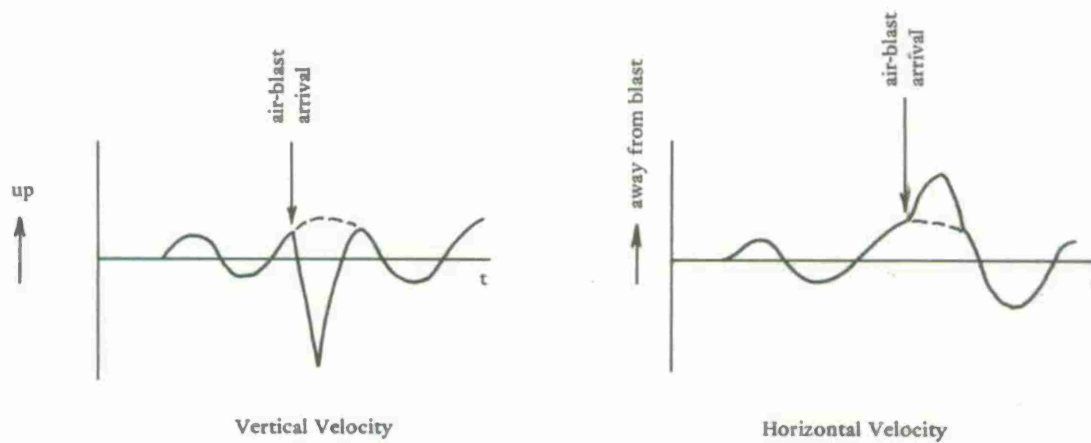


Fig 1b. Outrunning ground shock

PREDICTION METHODS

Approach

Initial efforts in this study were concentrated on a comprehensive search of available literature on ground shock from nuclear and non-nuclear explosions. A list of the publications reviewed is contained in the Bibliography. Most of the existing literature in this field is concerned with estimating the effects of nuclear explosions; however, as a result of the nuclear test ban treaty and recent advances in ground motion transducers and instrumentation, most reliable data have been obtained from high explosive detonations. This situation leads to the paradox that most analytical and empirical prediction methods were intended to predict nuclear explosion phenomenology, but most of the data used in verifying predictions for surface bursts were obtained from high explosive shots. Since (1) the energy density, (2) the partition of the energy among air blast, ground shock, heat, light, and radiation, and (3) the absolute magnitude of the energies are drastically different for nuclear explosions than for chemical explosions, correlations between the two are difficult.

The primary concern of the present study was to evaluate the ground shock effects of non-nuclear accidental explosions. Thus, the data used in this study were entirely from surface bursts of non-nuclear explosives. Ground shock data were obtained for detonations of one-half to one-half million kg (one to one million pounds) of TNT, and for scaled ranges from 0.2 to 24m/kg^{1/3} (0.5 to 60 ft/lb^{1/3}). The predominant charge configuration was a sphere tangent to and above the ground surface. Results from several half-buried spherical charges and a few hemispherical charges are also included in the data.

The initial data gathering efforts consisted of simply listing the charge configuration, yield, and ground media properties that were available. At each range for which data existed, ground shock data, air-blast overpressures, and air-blast impulses were recorded. Naturally, not all the desired data points were available for each instrumented range of each shot, but sufficient data were available to make reasonable correlations. Ground shock was recorded only for gages within about 1/2 meter (1 1/2 feet) or less below the ground surface. When reported data were tabularized, the investigator's interpretation of air-blast- or direct-induced portions of the waveform were accepted, unless anomalous points were noticed. In the latter cases, the information was not used, unless the nature of the motions could be determined from the published waveforms. In cases where direct data and derived data were available at the same point (e.g., velocity data and integrated acceleration data), both were used.

The data reduction process included converting data to consistent units and calculating scaled distances and other parameters used in developing the empirical equations. A review of References 2, 4, and 5 indicated that approximate analytical expressions adequately predict

peak air-blast-induced ground shock; consequently, the predominant effort in developing prediction methods was directed toward obtaining empirical equations for direct-induced ground shock. Constants for the empirical equations were developed using a standard least squares curve fitting technique.

Findings

References 2, 4, and 5 generally agree that the best estimates of air-blast-induced ground shock can be determined through one-dimensional wave propagation theory. For surface structures located on ground media in which the travel time required for a seismic wave to reflect from an underlying layer and return to the surface is longer than the response time of the structure, these expressions degenerate to very simple forms. Using this approach, the maximum vertical velocity at the ground surface, V_v , can be expressed as

$$V_v = \frac{P_o}{\rho c_p} \quad (1)$$

where P_o = peak side-on overpressure

ρ = mass density of the ground media

c_p = compression wave seismic velocity

The maximum displacement, D_v , is derived by integrating the above expression with respect to time; thus,

$$D_v = \frac{1}{\rho c_p} \int_0^{t_o} P(t) dt \quad (2)$$

The integral part of Equation 2 is simply the total positive phase overpressure impulse, which can be obtained from graphs in Reference 1.

Maximum vertical acceleration, A_v , is based on the assumption of a linear velocity increase during the rise time, t_d ; thus,

$$A_v = \frac{v_v}{t_d} \quad (3)$$

Reference 2 recommends the use of a rise time of 0.001 sec, which is independent of other blast parameters, and recommends increasing the resulting acceleration by 20% to account for nonlinearity during the rise time. Accelerations are usually expressed in multiples of g, the nominal acceleration of gravity.

The form of the expressions for estimating direct-induced motions was based on equations from Reference 2. In some cases a slight modification of the expressions was required to put the expressions into formats that were consistent with Reference 1. The primary concern was to express ground shock parameters in terms of the scaled range, $R_G/W^{1/3}$.

Reference 2 gives the following expression for estimating direct-induced vertical displacements

$$D_v = K_d W^{5/6} R_G^{-2/3} \quad (4)$$

where D_v = vertical displacement

K_d = empirical constant

W = yield

R_G = ground range

Dividing both sides by $W^{1/3} R_G^{1/3}$ gives

$$\frac{D_v}{W^{1/3} R_G^{1/3}} = K_d W^{3/6} R_G^{-1}$$

The right side of this equation can be expressed in terms of the scaled range if $W^{1/3}$ is used in place of $W^{3/6}$ on the right side. The expression then becomes

$$\frac{D_v}{W^{1/3} R_G^{1/3}} = K_d \left(\frac{R_G}{W^{1/3}} \right)^{-1}$$

This expression can be generalized if the exponent of the scaled range is allowed to be an arbitrary constant, n_d . Thus, the form of the empirical equation for direct-induced displacement is

$$\frac{D_v}{W^{1/3} R_G^{1/3}} = K_d \left(\frac{R_G}{W^{1/3}} \right)^{n_d} \quad (5)$$

The expression in Reference 2 for peak vertical velocity is

$$V_v = K_v W^{2/3} R_G^{-2} = K_v \left(\frac{R_G}{W^{1/3}} \right)^{-2} \quad (6)$$

This expression can be generalized without further modification to give

$$V_v = K_v \left(\frac{R_G}{W^{1/3}} \right)^{n_v} \quad (7)$$

The expression from Reference 2 for peak vertical acceleration is

$$A_v = K_a W R_G^{-4} \quad (8)$$

Multiplying both sides by $W^{1/3}$ gives

$$W^{1/3} A_v = K_a W^{4/3} R_G^{-4} = K_a \left(\frac{R_G}{W^{1/3}} \right)^{-4}$$

Generalizing this expression gives

$$W^{1/3} A_v = K_a \left(\frac{R_G}{W^{1/3}} \right)^{n_a} \quad (9)$$

The values of the constants k and n can be determined for non-nuclear explosions by using least squares curve fitting techniques for plots of scaled range versus the quantities on the left sides of Equations 5, 7, and 9.

Although test data exist for a variety of ground media, the literature search indicated that only the air-blast-induced ground shock could be quantitatively correlated with test results. The acoustic impedance appears to be the critical material parameter.

Direct-induced ground shock data were separated into three qualitative categories: dry soil, saturated soil, and rock. Attempts at further divisions or quantitative parametrization did not appear to provide better accuracy or precision in the prediction equations. In some cases, even the above distinctions were unnecessary. For example, the empirical equations for predicting direct-induced vertical velocities in different media did not vary significantly from the equation derived for all media lumped together. Thus, a single equation was used for all media. In cases where significant differences existed between empirical equations for different material categories, separate equations were recommended. Conversely, when insufficient data were available to justify a separate equation, the data were combined into a single equation.

Prediction Equations

Recommended equations for predicting air-blast-induced ground shock are presented in Table 1. These equations are intended to provide reasonable estimates of the air-blast-induced ground shock at the ground surface. They are based on the assumption that the ground medium properties are uniform for a distance below the surface equal to the wavelength of the pressure pulse in the medium. For design purposes, the gross motions of structures with shallow foundations can be assumed to be equal to these motions. Although this latter assumption is not strictly correct, it should provide estimates of structural ground shock environment that are at least as accurate as the prediction equations.

Figure 2 shows comparisons of the calculated and measured peak vertical air-blast-induced motions from high explosive field tests; these data were obtained primarily from References 6, 7, and 8. Points plotted above the 45 degrees equivalency lines on the graphs represent cases in which measured responses exceeded the predicted value. Except in the case of accelerations, the data tend to cluster around the equivalency lines. The scatter band for accelerations is almost an order of magnitude wide. In general, the prediction equation underestimates the accelerations for

Table 1. Recommended Prediction Equations for
Air-Blast-Induced Ground Motion

Vertical

$$D_v = \frac{1}{\rho c_p}$$

$$V_v = \frac{P_o}{\rho c_p}$$

$$A_v = \frac{1,200 P_o}{\rho c_p g}$$

Horizontal

$$D_h = D_v \tan \left[\sin^{-1} (c_p/U) \right]$$

$$V_h = V_v \tan \left[\sin^{-1} (c_p/U) \right]$$

$$A_h = A_v \tan \left[\sin^{-1} (c_p/U) \right]$$

For $\tan \left[\sin^{-1} (c_p/U) \right] > 1$, horizontal and vertical motions are approximately equal.

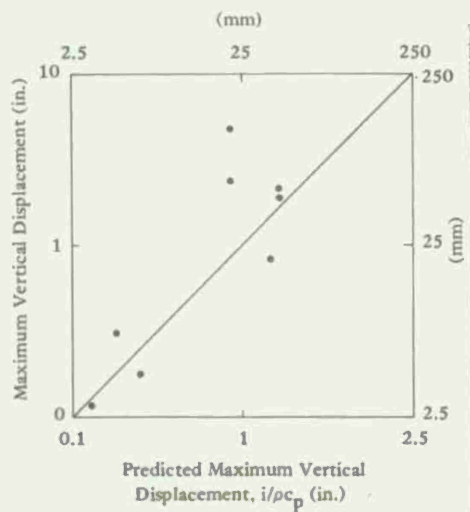


Fig 2a. Predicted and measured peak air-blast-induced displacements

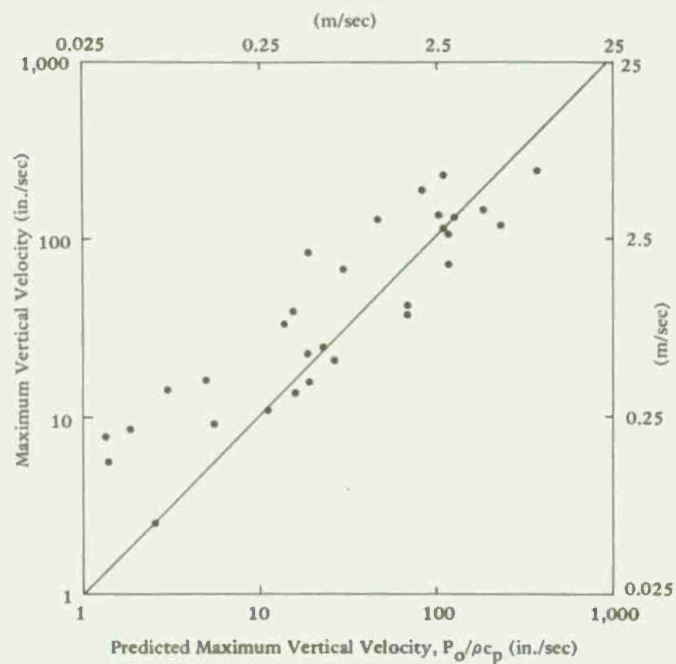


Fig 2b. Predicted and measured peak air-blast-induced velocities

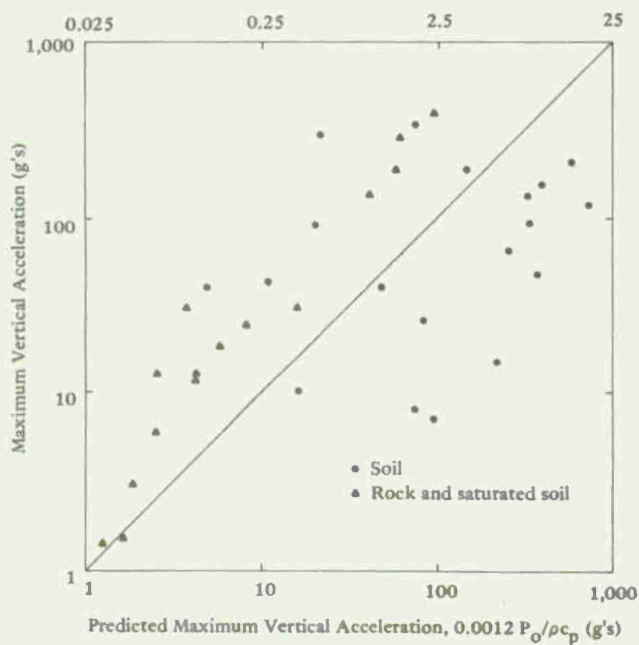


Fig 2c. Predicted and measured peak air-blast-induced accelerations

dry soil. The reasons for these differences are not clear; however, insufficient data are available to justify separate empirical equations. A conservative approach to design might be to use the recommended equation for air-blast-induced accelerations in dry soil and to double those values in other media.

Recommended equations for predicting direct-induced ground motions are presented in Table 2. These empirical equations were based on data from TNT detonations in spherical and hemispherical charge configurations near the ground surface. All of the experiments were conducted with unconfined charges on the bare ground surface. These equations represent the best fit to the available data from the reports indicated in the Bibliography.

Figure 3 shows the ground shock prediction equations plotted on graphs of ground motion data from three representative field tests (References 8, 9, and 10). Horizontal velocities from a 90,000-kg (100-ton) TNT burst on soil are shown in Figure 3a; Figure 3b shows vertical velocities from a 450-kg (1,000-pound) TNT detonation on a saturated soil site. Figure 3c shows measured horizontal accelerations and the corresponding prediction equation for a 90,000-kg (100-ton) detonation on a rock site. These figures indicate the prediction equations provide reasonable estimates of direct-induced ground shock maxima for a variety of media and yields. These comparisons were presented to indicate the general trend of the data with respect to the prediction methods; individual data points could differ from predicted values by as much as a factor of 10. In general, however, the data fall into reasonably narrow bands.

Part of the cause of the data scatter is the measurement technique. Accelerometers used in ground shock measurement have a tendency to pick up high-frequency stress-wave-induced accelerations and electronic noise. These noise peaks can add or cancel actual rigid body accelerations and lead to large data errors. Errors in displacement measurements arise from the fact that displacements must be calculated by integrating velocity data and that the integration process can cause an accumulation of errors. Velocity data for direct-induced ground shock are obtained directly from velocity gages that are relatively low-frequency, low-noise devices. The major source of error for velocity gages is gage tilting; this problem is not severe at the ranges and yields from which the data were obtained. Other variations result from yield variability and phenomenological anomalies.

DESIGN IMPLICATIONS

The ground shock phenomenology that has been discussed to this point must be viewed in the context of safety and design requirements. Therefore, the impact on inhabited building distances and interline magazine distances will be discussed, and design recommendations will be made for situations where ground shock effects can lead to safety problems.

Table 2. Recommended Prediction Equations* for Direct-Induced Ground Motion

Parameter	Media	Vertical		Horizontal
		SI Units	English Units	SI or English Units
Displacement	Rock	$\frac{D_v}{R_G^{1/3} W^{1/3}} = 3.7 \times 10^{-4} Z_G^{-1.3}$	$\frac{D_v}{R_G^{1/3} W^{1/3}} = 0.025 Z_G^{-1.3}$	$D_h = 0.5 D_v$
	Soil	$\frac{D_v}{R_G^{1/3} W^{1/3}} = 1 \times 10^{-3} Z_G^{-2.3}$	$\frac{D_v}{R_G^{1/3} W^{1/3}} = 0.17 Z_G^{-2.3}$	$D_h = D_v$
Velocity	All	$V_v = 0.95 Z_G^{-1.5}$	$V_v = 150 Z_G^{-1.5}$	$V_h = V_v$
Acceleration	All	$A_v W^{1/3} = 1,200 Z_g^{-2}$	$A_v W^{1/3} = 10,000 Z_G^{-2}$	
	Dry Soil			$A_h = 0.5 A_v$
	Wet soil & rock			$A_h = A_v$

*The units used in each set of equations are as follows:

Quantity	SI Units	English Units
D_v, D_h	m	in.
V_v, V_h	m/sec	in./sec
A_v, A_h	g	g
R_G	m	ft
W	kg	lb

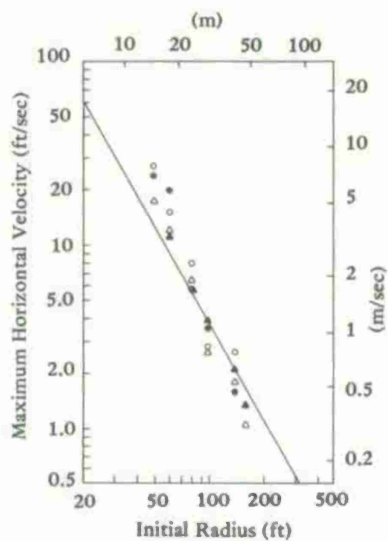


Fig 3a. Maximum direct-induced horizontal particle velocity; Distant Plain Event 6 (Ref 9)

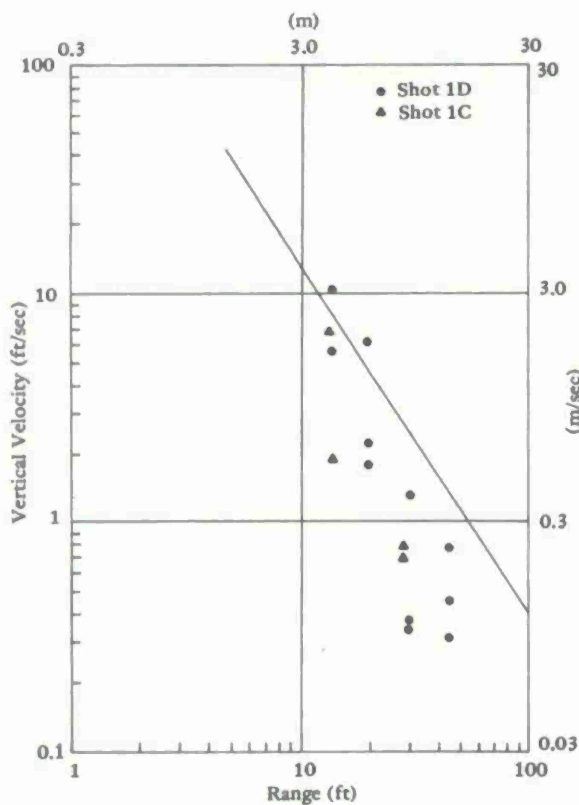


Fig 3b. PACE 450-kg (1,000-lb) tangent-above shot data, vertical velocity (Ref 8)

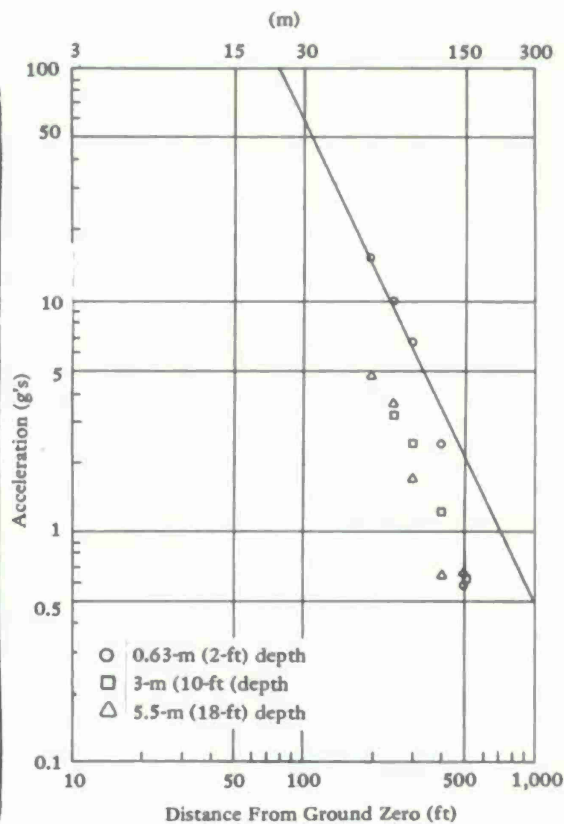


Fig 3c. Peak horizontal (outward) acceleration versus distance from the Mineral Rock Event (Ref 10)

Inhabited Buildings

A review of the literature revealed that the ground shock vulnerability of residential structures and, by inference, unhardened inhabited buildings in general can be defined in terms of peak ground shock velocity. Reference 11 gives the following criteria for damage prediction in inhabited buildings:

Damage	Peak Velocity (any direction)	
	(mm/sec)	(in./sec)
None	5	2.0
Minor	14	5.4
Major	19	7.6

Using the equations in Table 2, these velocities would be exceeded as a result of direct-induced ground shock at distances less than the following scaled distances:

Damage	Scaled Range	
	(m/kg ^{1/3})	(ft/lb ^{1/3})
None	6.9	17.3
Minor	3.6	9.2
Major	2.9	7.3

All of these distances are significantly less than the permissible inhabited building distances of 16 to 20 m/kg^{1/3} (40 to 50 ft/lb^{1/3}), and all are scaled distances at which air-blast and fragment vulnerability levels would be exceeded.

The vulnerability of inhabited buildings to air-blast-induced ground shock was evaluated by calculating the scaled ranges at which the peak velocity criteria were met for each of the three general classes of ground media. Material properties used for the calculations were:

Medium	(kg/m ³)	$\frac{\rho}{\text{lb-sec}^2/\text{ft}^4}$	(m/sec)	$\frac{c_p}{\text{ft/sec}}$
Soil	1,520	2.95	460	1,500
Saturated soil	2,000	3.88	1,520	5,000
Rock	2,560	4.97	4,000	13,000

The scaled ranges at which the various damage criteria were met were:

Damage	Soil		Saturated Soil		Rock	
	(m/kg ^{1/3})	(ft/lb ^{1/3})	(m/kg ^{1/3})	(ft/lb ^{1/3})	(m/kg ^{1/3})	(ft/lb ^{1/3})
None	5.7	14.3	2.7	6.8	1.5	3.9
Minor	3.4	8.6	1.7	4.3	1.0	2.5
Major	2.9	7.3	1.5	3.7	0.8	2.1

The resulting scaled distances for equivalent damage levels are less than those for direct-induced ground shock. Thus, the probability is small that air-blast-induced ground shock would control the design or permissible location of inhabited buildings.

Magazines

A second critical area in which ground shock effects might be significant is in the design of structures at the various permissible intermagazine distances. The relative severity of ground shock becomes greater at small scaled ranges, and structures located at those ranges are strong and massive to resist blast and fragment effects. In general, structures designed to survive these severe environments are not likely to be damaged by the associated ground shock. Reasons for the preceding generalization will be given by the following discussion, but until adequate data are available, ground shock effects should be checked in all designs.

Air-blast-induced ground shock occurs at the same time as the air-blast loading on aboveground structures. Since the ground tends to move downward and outward at the same time as the air blast is pushing the structure in the same direction, air-induced ground shock slightly decreases the loading on a structure. This effect is generally negligible. Thus, the effects of air-blast-induced ground shock can be neglected in the design of close-in structures, but as will be demonstrated later, they may provide a severe environment for the structure's contents.

Structural damage to aboveground facilities from direct-induced ground shock is not probable. Although very high accelerations are indicated for small explosive weights at intermagazine distances, these motions are of such high frequency and low energy content that little damage to practical size structures is expected. For example, at a scaled range of $0.5\text{m/kg}^{1/3}$ ($1.25\text{ ft/lb}^{1/3}$) and a charge of 0.5 kg (1 lb), air-blast- and direct-induced accelerations are greater than 6,000 g's, but maximum displacements are only 0.3 mm (0.1 in.).

For charges greater than about 50,000 kg (110,000 lb) direct-induced ground shock does not present a structural threat, because the accelerations are relatively low. The relatively large ground displacements that occur for large charge weights could, however, cause failure of external connections to structures. These displacements may cause relative motions at stiff utility connections to structures. If flexible or ductile connections are not provided, critical utilities, such as electrical power or water supply, could be severed, resulting in possible fire hazards. Relative motions, should be considered in selecting connection details.

Ground shock from accidental explosions could cause injury to personnel working near magazines or other areas of explosive hazards, even if the persons are protected from air-blast effects. A generally accepted shock tolerance level for a person standing with knees locked is 3 m/sec (10 ft/sec) maximum vertical velocity when accompanying

accelerations are greater than 20 g's (Reference 12). These criteria are shown graphically in Figure 4. In general, persons will not experience injury due to vertical ground shock when the combination of acceleration and velocity fall below and to the left of the injury threshold plotted in Figure 4. These criteria apply to upward motion of the floor and would, therefore, be the motions resulting from direct-induced ground shock. For downward displacements (air-blast-induced ground shock) the floor moves out from under the person, and the injury threshold is reached if the relative velocity between the person and the floor exceeds 3 m/sec (10 ft/sec).

Injury criteria for horizontal motions are more difficult to define, because the proximity of persons to solid objects cannot be predetermined. In general, horizontal accelerations of about 0.5 g are sufficient to knock a person off balance and cause injury as a result of the person striking a wall, a fixed object, or a sharp convex corner (Reference 13). The maximum horizontal acceleration that can be transmitted to a standing person through the floor of a structure is limited by the amount of force that can be transmitted through friction between a person's feet and the floor. Even in the most extreme cases the coefficient of friction is less than 1.0. Thus, horizontal accelerations are limited to 1 g, and the critical injury mechanism is impact when the person strikes the floor or other objects in a structure. Injury will generally occur when the impact velocity exceeds 3 m/sec (10 ft/sec) (Reference 12).

The overturning of heavy objects must also be considered in evaluating the vulnerability of persons to horizontal ground shock. Dynamic overturning moments for critical objects in a structure should be estimated or measured, and, if necessary, tie-down systems should be designed to prevent these objects from overturning onto personnel.

Ground shock is not a critical injury-producing mechanism for personnel who are exposed to air blast. Peak ground motions were estimated for the overpressure levels at which threshold and 50% eardrum rupture occur: 35 and 100 kPa (5 and 15 psi), respectively (Reference 1). Peak velocities at both ranges are at least an order of magnitude less than the injury thresholds. Although air-blast-induced vertical accelerations are between 4 and 13 g's, peak displacements are less than 25 mm (1 in.), so free-fall velocities greater than 3 m/sec (10 ft/sec) cannot be achieved. Ground shock would, therefore, contribute little to personnel injuries.

Explosives and mechanical or electrical equipment located within structures at intermagazine distances could be vulnerable to ground shock. These items are subjected to shock transmitted from the structure or mounting or to impact as a result of overturning. Reference 1 indicates that the latter is a primary consideration for explosives. Equipment that is hard mounted or otherwise attached to a structure should be evaluated with respect to the item's sensitivity to transmitted shock. Although explosive materials may not be sensitive to motions produced by ground shock, some sensitive items might trigger a detonation as a result of severe ground shock. These items should be shock-tested in the same manner as other mechanical or electrical equipment.

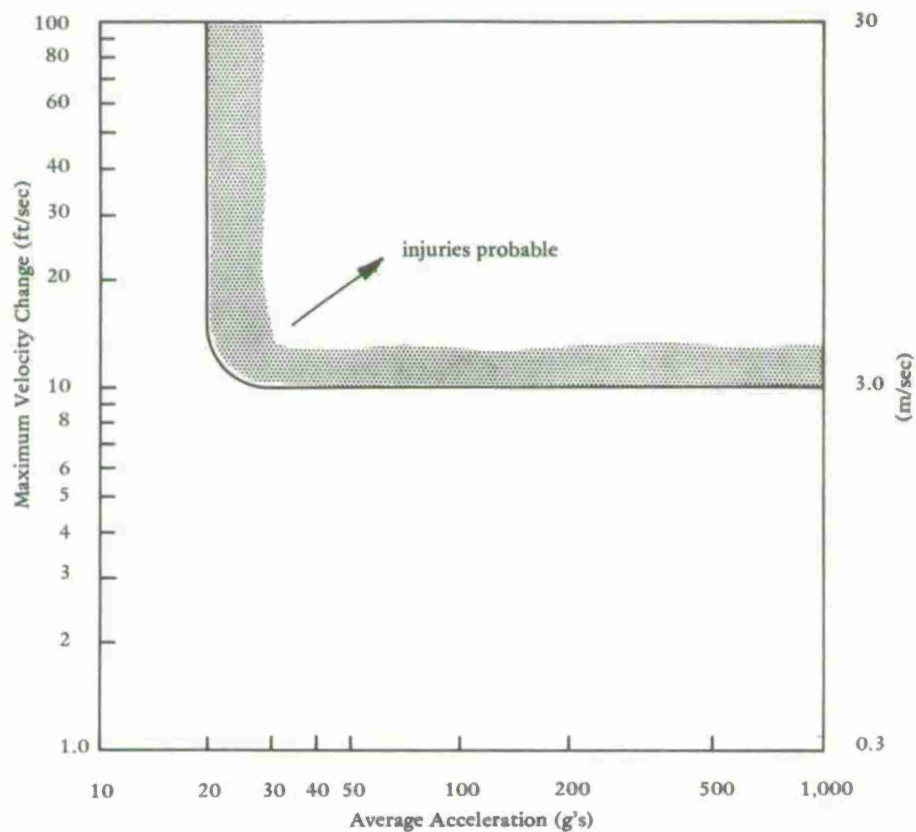


Fig 4. Tolerance of stiff-legged standing persons to short-duration vertical shock motions (Ref 12)

Specifically, fragility levels of sensitive items should be expressed in terms of shock spectra (as described in the next section), so a designer could properly select mounting or shock isolation systems.

Design Recommendations

The findings thus far have indicated that ground shock is not generally a critical parameter in the design of blast-hardened structures. Existing design methodologies which consider air-blast and fragment effects should provide adequate structural designs for most situations. However, the following additional steps are recommended to assure that personnel and equipment within are not vulnerable to ground shock effects.

The first step is to calculate the peak ground motions from the equations in Tables 1 and 2. Ground media data can usually be obtained from the site survey data. Media classification, density, and compression wave seismic velocity are the only necessary data. If only the media type is known, the approximate density and seismic velocity can be obtained from Tables 3 and 4, which have been extracted from Reference 2.

If the design criteria specify that the safety of personnel within a structure is to be considered, peak velocities and accelerations should be compared with the injury criteria described previously. In cases where the 3-m/sec (10-ft/sec) impact limit is exceeded, cushioning material can be used (Reference 1). Where overturning equipment is a potential injury mechanism, the equipment can be tied down to the floor or restraining devices can be provided to "catch" the equipment if it topples.

Equipment vulnerability can be evaluated by a relatively simple response spectrum approach. The response spectrum is a plot of the peak response of a series of single-degree-of-freedom oscillators versus the undamped natural frequency of the oscillator for a given base excitation. Thus, it describes the capability of the particular base excitation to excite systems of various natural frequencies. If the excitation waveform is precisely known, the response spectrum can be calculated. However, ground shock is characterized by a complex waveform about which little is known for any specific design case. Experience has shown that an envelope of the exact spectra for the individual possible ground motions can be estimated if the peak values of acceleration, velocity, and displacement are known.

Figure 5 shows an example of one method of plotting an estimated shock spectrum envelope. In this example, all scales are logarithmic. The natural frequency is plotted on the horizontal scale, and the pseudo-velocity is plotted on the vertical scale. Displacement and pseudo-acceleration axes are at 45 degrees to the primary axes. The terms pseudo-velocity and pseudo-acceleration are used to distinguish these values as spectral bounds rather than true motions. Response spectrum envelopes generally consist of displacement, velocity, and acceleration boundaries.

Table 3. Mass Density for Typical Soils and Rocks (After Ref 2)

Material	Mass density, ρ	
	kg/m^3	$(\text{lb-sec}^2)/\text{in.}^4$
Loose, dry sand	1,520	1.42×10^{-4}
Loose, saturated sand	1,920	1.79×10^{-4}
Dense, dry sand	1,760	1.65×10^{-4}
Dense, saturated sand	2,160	2.02×10^{-4}
Dry clay	1,200	1.12×10^{-4}
Saturated clay	1,760	1.65×10^{-4}
Dry, sandy silt	1,680	1.57×10^{-4}
Saturated, sandy silt	2,080	1.95×10^{-4}
Basalt	2,740	2.56×10^{-4}
Granite	2,640	2.47×10^{-4}
Limestone	2,400	2.25×10^{-4}
Sandstone	2,240	2.10×10^{-4}
Shale	2,320	2.17×10^{-4}
Concrete	2,400	2.25×10^{-4}

Table 4. Typical Seismic Velocities for Soils and Rocks (After Ref 2)

Material	Seismic Velocity	
	m/sec	in./sec
Loose and dry soils	180 to 1,000	7,200 to 39,600
Clay and wet soils	760 to 1,900	30,000 to 75,600
Coarse and compact soils	910 to 2,600	36,000 to 102,000
Sandstone and cemented soils	910 to 4,300	36,000 to 168,000
Shale and marl	1,800 to 5,300	72,000 to 210,000
Limestone-chalk	2,100 to 6,400	84,000 to 252,000
Metamorphic rocks	3,000 to 6,400	120,000 to 252,000
Volcanic rocks	3,000 to 6,700	120,000 to 270,000
Sound plutonic rocks	4,000 to 7,600	156,000 to 300,000
Jointed granite	2,400 to 4,600	9,600 to 180,000
Weathered rocks	600 to 3,100	24,000 to 120,000

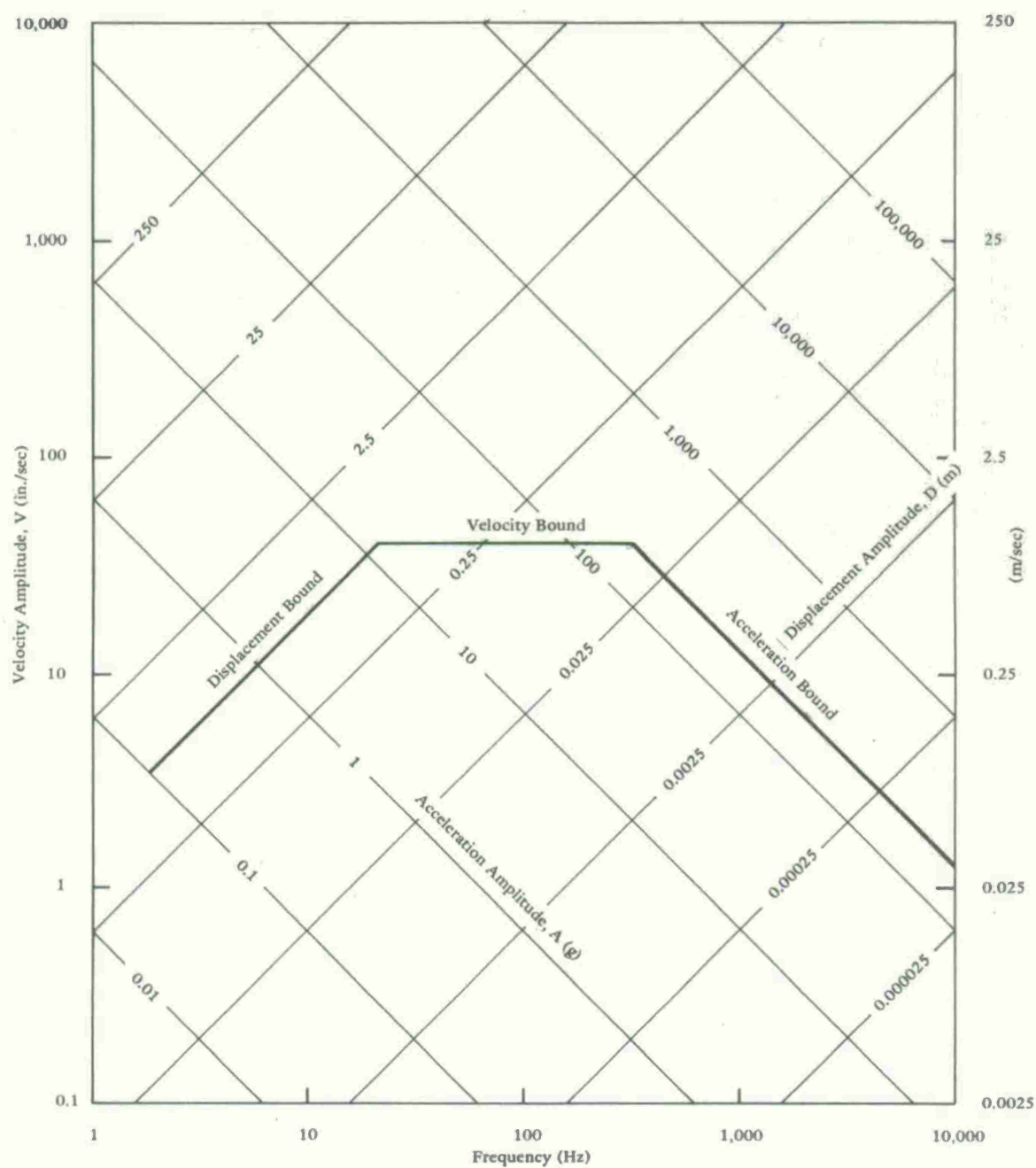


Fig 5. Typical shock spectrum plot

A recommended method for calculating response spectrum bounds for the evaluation of equipment vulnerability in blast-hardened structures is as follows:

1. Plot the displacement boundary at 1.6 times the peak displacement.
2. Plot the velocity boundary at 1.8 times the peak velocity.
3. Plot the acceleration boundary at 2.0 times the peak acceleration.
4. Go through steps 1 through 3 for both air-blast- and direct-induced motions, and plot the overall envelope.

The foregoing process will provide a spectrum envelope for ground shock along one axis, e.g., vertical motion. A numerical example for a simple problem is presented in the Appendix.

If data are available on the response spectra (fragility levels) for the equipment of concern, determine if the ground shock response spectra fall below the equipment fragility levels. If the ground shock response spectra are above those levels, the equipment will have to be shock isolated. If fragility levels are not known, the natural frequency can be estimated, and the response of the equipment can be obtained from the response spectrum. Critical elements of the equipment can then be analyzed for response to these shock values. Springs can be used to change the frequency of the equipment mounting, or energy-absorbing materials can be used to dampen the response. Details of shock isolation design are beyond the scope of the present effort.

DEFICIENCIES

The present effort was intended to provide some insight to the effects of ground shock on designing structures to resist accidental explosions. Although expressions have been presented for estimating the magnitude of ground shock and an approach to evaluating design implications has been presented, gaps exist in the data, and several questions remain unanswered. Some of these deficiencies are discussed in this section.

A primary limitation in the data used in developing ground shock prediction methods is that all of the data points were from uncased explosions over bare ground. In many design situations, such as explosive plants and magazines, incidents are most likely to occur in buildings or working areas that are on massive foundations. Although the effects of cased versus uncased explosions can be estimated, the effects of a structurally coherent slab below the explosive are not included in the present analysis. This effect will limit the credibility of the direct-induced ground shock predictions, but if the character of the air-blast

wave can be described at the range of interest, the air-blast-induced ground shock expressions should apply. The character of the modified direct-induced ground shock is not obvious for such incidents. While the magnitude of the ground shock could be reduced as a result of energy dissipated in the foundation slab, partial confinement by an enclosing structure could provide sufficient tamping to increase the proportion of total energy, coupled into the ground. Since the author knows of no experimental data relative to this problem, further study is necessary to assess qualitatively the effects of these parameters.

A simplifying assumption made in this study was that structures tend to move with and experience the same shock levels as the ground. The nature of a building's foundation might significantly alter the soil-structure interaction. For example, a building with a slab on grade would not respond the same as one with spread footings or piles. Structures with relatively high mass might also respond in a manner that is different from the surrounding ground. In general, one would expect high mass structures and structures with moderate to deep foundations to experience less severe air-blast-induced ground shock than those with shallow foundations. Thus, the present assumption is conservative.

The use of the response spectrum to estimate shock effects on structure contents is an approximate and highly simplified approach. More sophisticated levels of utilizing shock spectra are described in Reference 2 and elsewhere, but these methods generally require more detailed knowledge of the ground motion waveform. The approach presented in the current effort represents at least the same level of rigor as the equations for estimating peak ground motions.

The relatively large data scatter with respect to the best fit equations for direct-induced ground shock is partially due to errors in measurement and interpretation of data, but the most significant source of variation is the variability of ground shock phenomenology. A variation factor of two between measured quantities at the same range but different directions from the same event is not uncommon. Differences between peak velocity obtained from integrated accelerometer data and from a velocity gage located adjacent to it often differ by 50% or more. The overall range of data scatter is approximately a factor of five for accelerations, two for velocities, and three for displacements.

A further reason for the large scatter bands is that the ground media properties were not quantified. The broadly defined ground media categories tended to include media with wide variations in properties within single categories. Thus, some judgment must be exercised in selecting a particular equation. For example, a site with soft, weathered rock would behave more like a soil site than a rock site. In general, the rock category is intended for sites with relatively competent rock near the surface. The soil category is intended for soil sites with relatively low water tables, and the saturated soil model is intended for sites with water tables at or within a few meters of the surface.

Despite the foregoing deficiencies, the discussion and information presented here should provide a rational basis on which the evaluation of

ground shock effects can be based. The acquisition of additional data or more sophisticated analyses may improve the precision and accuracy of the prediction methods, but the need for a quantitative approach to the consideration of ground shock effects has been established.

RECOMMENDATIONS FOR FURTHER STUDY

Of primary concern in further studies of ground shock effects is the acquisition of data that are pertinent to the specific problem of accidental explosions. Existing data were obtained from actual or simulated nuclear weapon detonations in which uncased and unconfined explosive charges were detonated over exposed soil or rock. However, a major area of interest in accidental explosions is the problem of detonations in explosives manufacturing, storing, or handling facilities. In many cases potential detonations are partially or almost totally confined within a structure. Confining structures are generally massive to limit the blast and fragmentation effects, and these structures may also limit the amount of explosive energy transmitted to the ground and, thus, limit ground shock effects. It is also possible that the confining structures could provide a tamping effect and increase the energy transmitted to the ground. Tests and analyses should be conducted to evaluate the relative significance of each phenomenon. The ultimate goal would be to develop a method of determining an effective charge weight for ground shock effects from partially confined detonations. This effort would provide an improved approach to the prediction of ground shock environment.

Studies of methods for estimating the effective charge distance are also desirable. For charge weights in the usual range of interest various portions of a structure could be at significantly different scaled ranges. For example consider a 15-meter-long (50 ft) structure, the front of which is at a scaled range of $4 \text{ m/kg}^{1/3}$ ($10 \text{ ft/lb}^{1/3}$) from a 230-kg (500-lb) charge. The rear of the structure would be at a scaled range of $6.5 \text{ m/kg}^{1/3}$ ($16.3 \text{ ft/lb}^{1/3}$). The front would experience a maximum vertical direct-induced velocity of 0.12 m/sec (4.7 in./sec), and the rear would experience only 0.06 m/sec (2.3 in./sec) vertical velocity. If the structure acts as a rigid body with various excitations along its length, complex motions may result, and each area of the structure may experience significantly different motions than the adjacent ground media. Since a designer would like to use a single set of ground shock criteria for an entire structure, his tendency would be to select either a worst case or an average. A study should be undertaken to develop a rational method by which a designer could select an effective ground range for such cases.

Data for estimating effective charge weights and for further refining the prediction equations could be obtained if ground motion instrumentation were included in all tests in which accidental explosions are simulated. It would be beneficial to have measurements in the structure at locations of primary interest and corresponding measurements at the

same range in the ground medium. Thus, the assumptions regarding free-field versus structure motions could also be evaluated. The measurement of shock at locations of critical equipment would also provide useful design information.

Standard electronic acceleration and velocity transducers are available for obtaining time histories of ground shock effects. Records of the transducer outputs can be integrated to provide displacement-time histories. The data can also be processed to estimate the response spectrum for a given location. The response spectrum can also be obtained from reed gages (Reference 14). A reed gage consists of a series of cantilevered springs or reeds with a mass on the end of each reed. Several reeds with different natural frequencies that cover the range of interest are mounted in a gage. In principle, each reed acts as a single-degree-of-freedom oscillator. The peak displacement for each reed is determined from scratch marks made by a scribe mounted on each reed, and the response spectrum can then be plotted using the frequency-displacement data.

Effort should be devoted toward developing methods of protecting persons within structures that could be subjected to severe ground shock. This effort should include improved designs for interior attachments to the walls and ceilings, and present practices for installing heavy equipment should be reviewed. In addition to developing design improvements to prevent injuries from falling objects, concepts are needed for minimizing the possibility of injury to persons who might be physically displaced as a result of ground shock. A study of inexpensive concepts for shock-isolated floors might provide cost-effective approaches to protecting both equipment and personnel.

A review of munitions and explosives storage practices should also be made. The possibility exists that a severe ground shock environment could dislodge live munitions from storage racks, and the resulting fall might detonate the explosives. This is one critical area in which ground shock could be a more severe environment than blast or fragmentation. Since drop and shock sensitivity of munitions are usually known, the principal goal of the study should be to determine the nature of the ground shock that would dislodge the munitions from their storage racks. The shock transmitted through the structure and the storage rack should also be studied to determine if primary shock is more critical than drop sensitivity.

CONCLUSIONS

The purpose of this study was to determine the effects of ground shock from accidental explosions on structures and their contents. A major portion of the effort was the development of semi-empirical equations for predicting ground shock phenomenology. Equations for predicting ground shock as a function of explosive weight, distance from the explosions, and ground media properties have been presented. These

equations were used to evaluate the design implications of ground shock effects. The study indicated that although ground shock, per se, is not a critical parameter for structural survivability, it could affect the survivability of a structure's contents, such as personnel, equipment, or munitions. A design approach by which the effects of ground shock can be determined is presented in the report.

ACKNOWLEDGMENT

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APPENDIX
SAMPLE PROBLEM



Appendix

SAMPLE PROBLEM

The use of the ground shock prediction methods presented in this report can best be illustrated by a specific example. This Appendix contains a fictitious problem whose solution process illustrates the methodology.

PROBLEM STATEMENT

A rocket engine test stand is located in an open area that is 15 m (49 ft) from a hardened control and instrumentation building. Should the engine explode, the equivalent TNT yield would be 300 kg (660 lb). The soil under the test area and control building is dense dry sand with a mass density of $1,520 \text{ kg/m}^3$ ($0.000142 \text{ lb-sec}^2/\text{in.}^4$) and a seismic compression wave velocity of 630 m/sec ($25,000 \text{ in./sec}$). The structure has been designed for blast and fragment resistance.

Calculate explosion parameters:

Scaled Range

$$\begin{aligned} Z_G &= \frac{R_G}{W^{1/3}} = \frac{15}{300^{1/3}} = 2.24 \text{ m/kg}^{1/3} \\ &= \frac{49}{660^{1/3}} = 5.63 \text{ ft/lb}^{1/3} \end{aligned}$$

Overpressure - from Reference 1 assume a hemispherical surface charge

$$P_0 = 214 \text{ kPa (31 psi)}$$

Impulse

$$i = 0.96 \text{ kPa-msec (0.14 psi-msec)}$$

Shock front velocity

$$U = 610 \text{ m/sec (24,000 in./sec)}$$

Duration

$$t_0 = 10.5 \text{ msec}$$

Arrival time

$$t_A = 13.5 \text{ msec}$$

Arrival time of direct-induced ground shock

$$t_D = \frac{15 \text{ m}}{630 \text{ m/sec}} = 0.024 \text{ sec} = 24 \text{ msec}$$

These calculations indicate that the structure is located in the superseismic region where the air blast arrives before the ground shock. Since the direct-induced ground shock does not arrive until the air blast has passed, the two ground shock components can be considered independently.

AIR-BLAST-INDUCED GROUND SHOCK

Vertical Motions

Displacement

$$D_V = \frac{i}{\rho c_p} = \frac{0.96}{1,520 \times 630} = 1 \times 10^{-6} \text{ m}$$

$$\left(= \frac{0.140 \times 0.001}{0.000142 \times 25,000} = 4 \times 10^{-5} \text{ in.} \right)$$

Velocity

$$V_V = \frac{P_o}{\rho c_p} = \frac{214,000}{1,520 \times 630} = 0.22 \text{ m/sec}$$

$$\left(= \frac{31}{0.000142 \times 25,000} = 8.7 \text{ in./sec} \right)$$

Acceleration

$$A_V = \frac{1,200 P_o}{\rho c_{pg}} = \frac{1,200 \times 214,000}{1,520 \times 630 \times 9.8} = 27 \text{ g's}$$

$$\left(= \frac{1,200 \times 31}{0.000142 \times 25,000 \times 32.2 \times 12} = 27 \text{ g's} \right)$$

Horizontal Motions

Since the seismic compression wave velocity is greater than the shock front velocity at this range, horizontal motions due to air blast are approximately equal to the vertical motions.

DIRECT-INDUCED MOTIONS

Vertical Motions

Displacement

$$\begin{aligned} D_v &= 0.001 R_G^{1/3} W^{1/3} Z_G^{-2.3} \\ &= 0.001 (15)^{1/3} (300)^{1/3} (2.24)^{-2.3} = 0.0026 \text{ m} \\ &\left(= 0.17 (49)^{1/3} (660)^{1/3} (5.63)^{-2.3} = 0.10 \text{ in.} \right) \end{aligned}$$

Velocity

$$\begin{aligned} V_v &= 0.95 Z_G^{-1.5} = 0.95 (2.24)^{-1.5} = 0.28 \text{ m/sec} \\ &\left(= 150 (5.63)^{-1.5} = 11.2 \text{ in./sec} \right) \end{aligned}$$

Acceleration

$$\begin{aligned} A_v &= \frac{1,200 Z_G^{-2}}{W^{1/3}} = \frac{1,200 (2.24)^{-2}}{300^{1/3}} = 36 \text{ g's} \\ &\left(= \frac{10,000 (5.63)^{-2}}{660^{1/3}} = 36 \text{ g's} \right) \end{aligned}$$

Horizontal Motions

For soil, horizontal and vertical motions are about equal except for direct-induced acceleration. Thus,

$$A_h = 0.5 A_v = 18 \text{ g's}$$

GROUND SHOCK PARAMETERS

Summarizing the estimated ground shock parameters

<u>Parameter</u>	Air Induced	Direct Induced
	<u>Vertical and Horizontal</u>	<u>Vertical/Horizontal</u>
D	1×10^{-6} m (4×10^{-5} in.)	0.0026 m (0.1 in.)/same
V	0.22 m/sec (8.7 in./sec)	0.28 m/sec (11.2 in./sec)/same
A	27 g's	36 g's/18 g's

Calculate the response spectrum bounds

$$D' = 1.6D$$

$$V' = 1.8V$$

$$A' = 2A$$

<u>Parameter</u>	Air Induced	Direct Induced
	<u>Vertical and Horizontal</u>	<u>Vertical/Horizontal</u>
D'	1.6×10^{-6} m (6.4×10^{-5} in.)	0.0042 m (0.16 in.)/same
V'	0.4 m/sec (15.7 in./sec)	0.5 m/sec (20.2 in./sec)/same
A'	54 g's	72 g's/36 g's

The worst case shock spectra, which is vertical direct-induced, is plotted in Figure A-1. Also plotted in this figure is a hardness level for one type of oscilloscope. The hardness is the shock spectra of a specific test environment that the equipment has survived. In this example, the hardness of the oscilloscope is significantly above the response spectra from the accidental explosion, and, thus, the equipment would be expected to survive without special shock mounting.

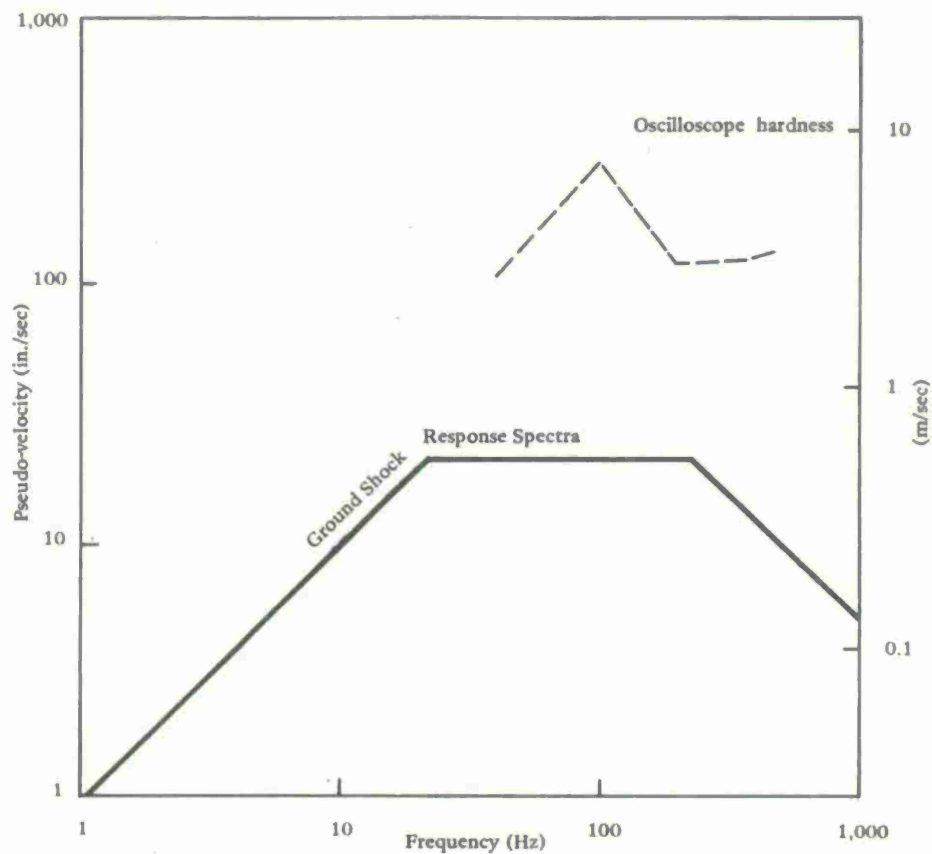


Fig A-1. Ground shock spectra



"List of Symbols"

A_h	Horizontal acceleration (g)
A_v	Vertical acceleration (g)
c_p	Dilational velocity of ground medium (m/sec, in./sec)
D_h	Horizontal displacement (m, in.)
D_v	Vertical displacement (m, in.)
i	Unit positive impulse (Pa-sec, psi-sec)
K	Empirical constant; subscripts d, v, a, are for displacement, velocity, and acceleration.
P_o	Peak overpressure (Pa, psi)
$P(t)$	Overpressure as a function of time
R_G	Ground range (m, ft)
ρ	Mass density of ground medium (kg/m^3 , $\text{lb-sec}^2/\text{in.}^4$)
t	Time (sec)
t_A	Arrival time of air blast
t_D	Arrival time of direct-induced shock
t_d	Rise time to peak overpressure (sec)
t_o	Duration of positive phase of overpressure (sec)
U	Shock front velocity (m/sec, in./sec)
V_h	Horizontal velocity (m/sec, in./sec)
V_v	Vertical velocity (m/sec, in./sec)
W	Charge weight or mass (kg, lb)
Z_G	Scaled ground range = $R_G/W^{1/3}$ ($\text{m/kg}^{1/3}$, $\text{ft/lb}^{1/3}$)

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